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Mutual coupling between slots in planar waveguide slotted array antenna

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Abstract Planar waveguide slotted array antennas offer extremely low sidelobe and controlled aperture excitation Lightweight, geometric simplicity and reliability make such arrays very useful for airborne radar application In large arrays with number of slots placed close to one another, the effect of mutual coupling is predominant Mutual coupling between slots affects the slot performance and antenna pattern In this paper an attempt is made to characterize a slot in the neighbourhood of a large number of longitudinal shunt slots in a Ka-band array. Improved array performance with better input match is achieved by minimization of mutual coupling effects by finding new slot lengths and offsets

Keywords : Mutual coupling, slotted array antenna

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1. Introduction

High performance radar requires microwave antennas that are large in terms of wavelength. The advantage of planar array of radiating elements over parabolic reflectors is that the antenna design dictates the distribution when each element is fed with correct amplitude and phase. This type of antenna is very useful in applications with narrow beamwidth and low sidelobe level. Most of the design techniques available for planar arrays, illustrates the slot characteristics in isolation [1]. For large arrays the effect of neighbouring slots on each slot cannot be ignored. Because of mutual coupling effects, the input impedance of a radiating antenna when used as an element of an array is different from its impedance value when the same antenna is isolated. Furthermore, this difference between impedance value may result in errors in the desired pattern, in increased sidelobe level, or in array mismatch. The amount and type of error introduced depends also on the means by which the array is fed [2].

The theory of mutual impedance is well established with dipoles. It has been reported to be efficiently used for small arrays in X-band. In this it is proposed that the same technique can be extended to larger arrays at Ka-band under certain assumptions. Such an analysis is of utmost importance at this band considering the mechanical and fabrication tolerances.

2. Theory

The mutual impedance between a point $X(0, y, z + \zeta 2)$ on the axis dipole A centered at $(0, y, z)$ and dipole B centered at $(0, 0, 0)$ is written as [3]

$$Z_{12} = \frac{j30}{\sin kl_1 . \sin kl_2} \int_{l_1}^{l_1} e^{-jkr_1} + \frac{e^{-jkr_2}}{r_2} - 2\cos kl_1 \frac{e^{-jkr}}{r} \times \sin k(l_2 - |\zeta_2|) d\zeta_2, \quad (1)$$

where l_1 and l_2 are lengths of the dipoles and r, r_1, r_2 are the distances from point X to center, top and bottom edge of dipole B. The value of Z_{12} is clearly influenced by the length of the dipoles. Under the assumptions that the dipoles are slender and not too close to each other, the field of one in the vicinity of the other is negligibly different from what one would compute by collapsing the current distribution onto the dipole axis. Also, the variation of this field over the surface of the other dipole is negligibly different from the variation of this field along the axis of the other dipole. For these reasons, under the stated assumptions it does not matter what the cross-sectional shapes of the dipoles are. Eq. (1)

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can be used to compute Z_{12} between strip dipoles as well as between cylindrical dipoles, as long as the slenderness criteria are met. Therefore, this paper proposes that the dipole theory can be extended to large slotted arrays at Ka-band under the following assumptions :

(i) Slenderness ratio ($l/w \geq 10$).
(ii) Slots are parallel.
(iii) All slots are centre fed.
(iv) Resonantly spaced ($\lambda g/2$ apart).
(v) Radiating slots in common waveguide.
(vi) Mode voltage has a common value.

In order to calculate the mutual impedance, we start with the basic design for waveguide slotted array antennas which consists of a planar array of longitudinal shunt slots which is fed by a main line waveguide transversely running across the back of the array. Coupling slots in the main waveguide are used to energise the branch lines. It is also assumed that the slots are resonantly placed. The design equations are :

$$\frac{Y^a_{mn}}{G_0} = K_1 f_{mn} \sin kv(x_{mn}) \frac{Y^s_{mn}}{V_{mn}} \tag{2}$$

and
$$\frac{Y^a_{mn}}{G_0} \quad \frac{K_2 f^2_{mn}}{Z^a_{mn}} \tag{3}$$

where $K_1 = j\left[-\frac{8}{\pi^2 \eta G_0} \cdot \frac{a/b}{\beta/k}\right]^{1/2}$

$$K_2 = \frac{292(a/b)}{0.61\pi(\beta/k)}$$

$$f_{mn} = \frac{\cos \beta l_{mn} - \cos kl_{mn}}{\sin kl_{mn}} \cdot \sin \frac{\pi x_n}{}$$

Where Y^a_{mn}/G_0 is the normalised admittance and a, b are waveguide broad wall and narrow wall dimensions β, η, k are contants. The double notation is used to indicate mth slot in nth branch line waveguide, V^s_{mn} is the voltage of the corresponding slot, l_{mn} is its length and x_{mn} its offset. Active admittance Z^a_{mn} of mnth equivalent loaded slot is the sum of its self impedance and mutual impedance. When the above equations are used one must assume an initial set of slot lengths and offsets to compute the initial mutual impedance values [4].

3. Design procedure

Ignoring mutual coupling, a waveguide slotted planar array was designed at Ka-band consisting of ten branch line waveguides with over 600 slots. Initial lengths and offsets was obtained from the preliminary design of the planar array choosing each slot to be self resonant with the proper distribution of conductances to ensure the proper pattern and input match. The synthesized pattern is shown in Figure 1. Once the selection of the initial values of slot lengths and offsets are done, eq. (1) can be used to compute all the mutual impedances between the dipoles in an equivalent array. The initial design data of every isolated slot can be

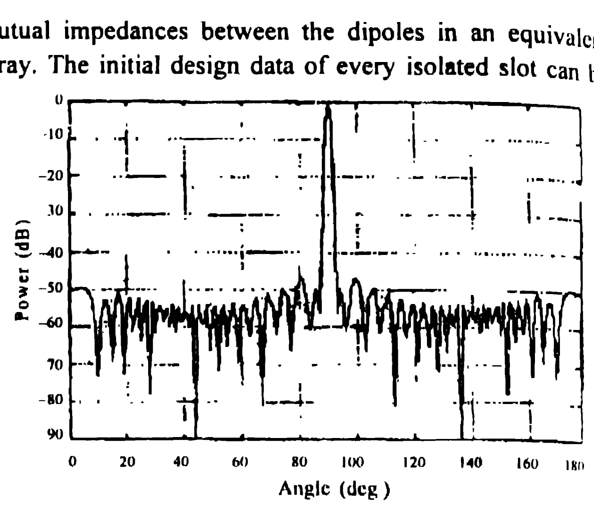

Figure 1. Synthesized array pattern

represented by a family of curves which is extremely useful for computational purposes. Plots of these curves are shown in Figures 2–5. It is important to note that all four curves are simple in form and can be easily polyfitted.

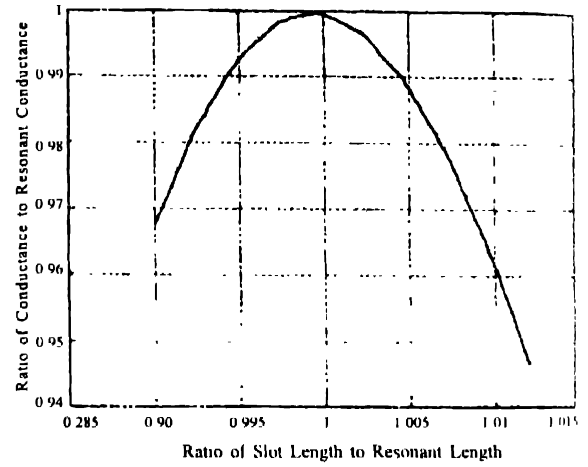

Figure 2. Normalised conductance *versus* resonant length for shunt slots

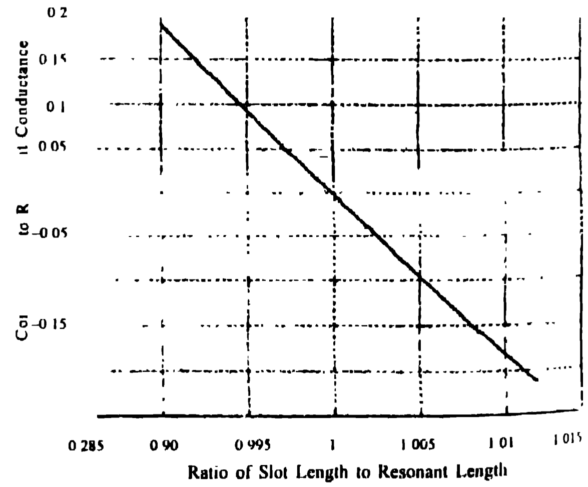

Figure 3. Normalised susceptance *versus* resonant length for shunt slots

These polyfitted functions together with the values of mutual impedance, eq. (2), eq. (3) and desired array excitation, permit computation of a set of starting values for the mutual coupling terms. This design procedure was carried out for equiphase slot voltage distribution. The effect of mutual coupling between the slots modifies the slot admittance and makes it non-resonant. Searching for the length-offset combination to make the active admittance purely real can minimize this effect. These modified lengths and offsets should be judiciously chosen to give the proper slot voltage distribution. Also sum of the normalized active admittance has to be unity (end-fed) or two (center-fed) since it the input match condition.

The entire design procedure involves complex and tedious calculations because it takes into account the effect of all slots on every single slot. A computer program has been

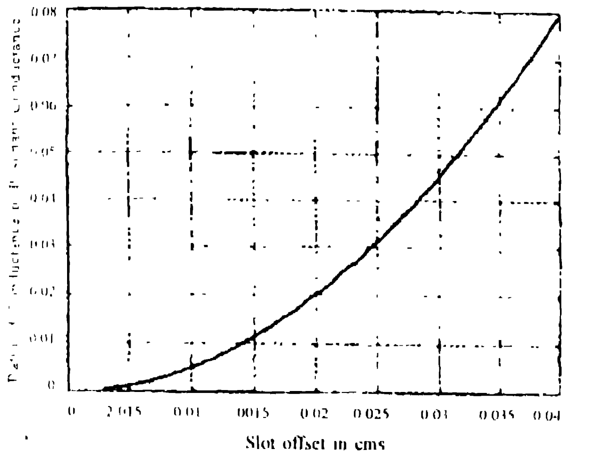

Figure 4. Normalised resonant conductance *versus* offset for shunt slots

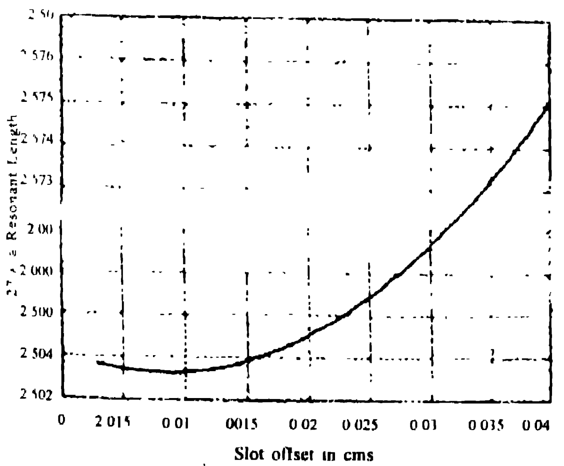

Figure 5. Resonant length *versus* offset for shunt slots.

developed to compute accurately the mutual impedance terms and finally arrive at the corrected slot length and offset. Several iterations for lengths and offsets are carried out until the variations are within the fabrication tolerances.

4. Discussion

The theoretically simulated azimuth patterns shown in Figure 6 clearly points out that effect of mutual coupling is predominant at the end channel compared to center channel. Figure 7 shows the comparison between the array pattern detoriation due to mutual coupling and pattern after

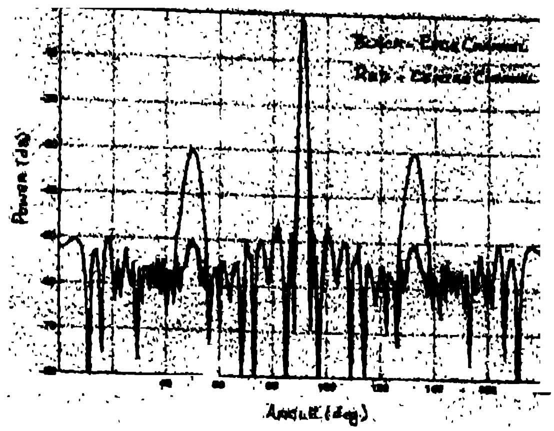

Figure 6. Effect of mutual coupling at center and edge of the array.

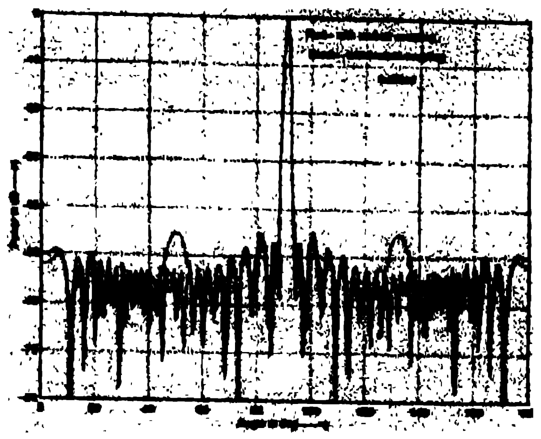

Figure 7. Array pattern (with mutual coupling and its correction)

cancellation of mutual coupling. The corrected pattern is matching closely with the synthesized pattern Figure 1. The simulation studies shows that no slot in the array is self resonant. Each slot has to be detuned appropriately to make the individual active admittance resonant. In a rectangular grid structure, symmetry in length and offset is observed in the 1st and 3rd and 2nd and 4th quadrants. Also effect of mutual coupling at edge of the array is predominant than at center of the array. When initial values of length and offset are chosen close to the desired conductance and input match, variation in final lengths and offsets are within 5% after minimization of mutual coupling. In such cases a single iteration would be sufficient. Several iterations may be required when the initial offsets are chosen arbitrarily without any taper in positions of the slots. A single channel of the array including correction for mutual coupling was fabricated and tested. The results are shown in Figure 8.

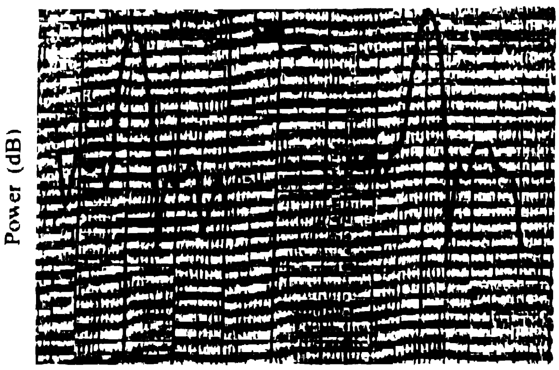

Figure 8. Measured pattern at Ka-band

Improved performance is expected with a new piece which is currently under fabrication with better mechanical tolerences. Experimental work is being carried on to prove it for planar arrays in this band.

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